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Ablation Effects in Oxygen-Lead Fragmentation at 2.1 GeV/Nucleon

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INTRODUCTION

With the advent of the Space Transportation System and the era of career astronauts, who will spend appreciable portions of their careers in space, the problem of providing radiation protection increases in importance (ref. 1). For career astronauts and long-duration missions, the high-energy heavy-ion (HZE) component of galactic cosmic rays will become of major radiobiological significance, especially for nonregenerative tissues (ref. 2). Since the range of these particles is large compared with a typical spacecraft wall thickness, nuclear attenuation and fragmentation appears to be a possible means of protection.

In this work, initial estimates of fragmentation cross sections for a typical cosmic ray nucleus (^{16}O at 2.1 GeV/nucleon) colliding with a heavier target nucleus (^{208}Pb) are made and compared with experimental results (ref. 3). The fragmentation process is analyzed by using an abrasion-ablation collision model. The abrasion formalism utilized is described in detail in references 4 through 7. In order to complete our initial efforts at describing the fragmentation process, we adopted a simple ablation formalism where the excited projectile prefragment, which remains after the abrasion step, is treated as a compound nucleus and allowed to statistically decay by particle evaporation. The prefragment excitation energy is determined from the geometric "clean cut" abrasion-ablation model of Bowman, Swiatecki, and Tsang (ref. 8). The compound nucleus particle evaporation probabilities are calculated by using the Monte Carlo program EVAP-4, developed at Oak Ridge National Laboratory (ref. 9). The resultant theoretical predictions are also compared with the predictions obtained from the geometric clean-cut model (ref. 8).

PROJECTILE FRAGMENTATION

The HZE particle fragmentation is assumed to take place in a two-stage formalism called the abrasion-ablation model. In this model, the projectile nuclei, moving at relativistic speeds, collide with stationary target nuclei. Those portions of their nuclear volumes which overlap are sheared away by the collision. This is the abrasion step. The remaining projectile piece, called a prefragment, continues its trajectory with essentially its precollision velocity. As a result of the abrasion process, the prefragment is in an excited state and decays by the emission of gamma radiation and/or the evaporation of nuclear particles (ablation). The resultant isotope is the nuclear fragment whose cross section is measured. The abrasion part of the collision process is often analyzed from classical geometric considerations (refs. 8 and 10) or by using formal quantum scattering theory (refs. 4 to 7 and 11). The ablation part of the process may be analyzed by calculating the prefragment deexcitation through geometric arguments (ref. 8) or more sophisticated methods based upon Monte Carlo or intranuclear cascade techniques (refs. 10 through 13).

Abrasion Cross Sections

The cross sections σ_m for abrading m nucleons from the ^{16}O projectile were calculated by means of the quantum mechanical methods given in references 5 and 7. The appropriate oxygen and lead nuclear distribution parameters and nucleon-nucleon scattering parameters were taken from reference 14. The results are displayed in table I. (The symbols used in this paper are defined in a list after the references.) If n of the abraded nucleons are neutrons and z are protons, the

TABLE I.- OPTICAL MODEL ABRASION CROSS SECTIONS FOR THE REACTION $^{16}O + ^{208}Pb \rightarrow m + X$

[Incident kinetic energy is 2.1 GeV/nucleon]

Number of abraded nucleons, m	Abrasion cross section, σ_m, mb
1	404
2	226
3	166
4	136
5	118
6	108
7	102
8	98
9	98
10	100
11	105
12	115
13	133
14	172
15	284
16	964

resultant abrasion cross section, σ_{nz} can be obtained from σ_m by using a hypergeometric distribution

$$\sigma_{nz} = \frac{\binom{N}{n}\binom{Z}{z}}{\binom{A}{m}} \sigma_m \tag{1}$$

where N is the total neutron number, Z is the total proton number, and the mass number is

$$A = N + Z \tag{2}$$

It should be noted that the assumption of a hypergeometric distribution could result in inaccuracies, since it assumes there is no correlation at all between neutron and proton distributions, and hence could lead to such unphysical results as abrading all neutrons or protons from a nucleus while leaving the remaining fragment intact.

Prefragment Excitation Energies

The excitation energy of the projectile prefragment following abrasion of m nucleons is calculated from the clean cut abrasion formalism of references 8 and 10. For this model, the colliding nuclei are assumed to be uniform spheres of radii R_i $(i = P,T)$. In the collision, the overlapping volumes shear off so that the resultant projectile prefragment is a sphere with a cylindrical hole gouged out of it. The excitation energy is then determined by calculating the difference in surface area between the misshapen sphere and a perfect sphere of equal volume. This excess surface area Δ is given by (ref. 10)

$$\Delta = 4\pi R_P^2\left[1 + P - (1 - F)^{2/3}\right] \tag{3}$$

where for ^{16}O (R_P = 3.32 fm) and ^{208}Pb (R_T = 7.04 fm), we have (ref. 10)

$$P = 0.125(\mu\nu)^{1/2}\left(\frac{1}{\mu} - 2\right)\left(\frac{1 - \beta}{\nu}\right)^2 - 0.125\left[0.5(\mu\nu)^{1/2}\left(\frac{1}{\mu} - 2\right) + 1\right]\left(\frac{1 - \beta}{\nu}\right)^3 \tag{4}$$

and

$$F = 0.75(1 - \nu)^{1/2}\left(\frac{1 - \beta}{\nu}\right)^2 - 0.125\left[3(1 - \nu)^{1/2} - 1\right]\left(\frac{1 - \beta}{\nu}\right)^3 \tag{5}$$

with

$$\nu = \frac{R_P}{R_P + R_T} \tag{6}$$

$$\beta = \frac{b}{R_P + R_T} \tag{7}$$

and

$$\mu = \frac{1}{\nu} - 1 = \frac{R_T}{R_P} \tag{8}$$

Equations (4) and (5) are valid when the collision is peripheral (i.e., the two nuclear volumes do not completely overlap). For this case, the impact parameter b is restricted such that

$$R_T - R_P \leqslant b \leqslant R_T + R_P \tag{9}$$

If the collision is central, then the projectile nucleus volume completely overlaps the target nucleus volume ($b < R_T - R_P$), and all the projectile nucleons are abraded. In this case, equations (4) and (5) are replaced by

$$P = -1 \tag{10}$$

and

$$F = 1 \tag{11}$$

and there is no ablation of the projectile, since it was destroyed by the abrasion. If the excess surface area is used from equation (3), the excitation energy is

$$E_{exc} = \Delta \bullet E_s \tag{12}$$

where $E_s = 0.95\ \mathrm{MeV/fm^2}$ is the nuclear surface energy coefficient (refs. 8 and 10) from the liquid drop model of the nucleus.

Ablation Factors

Depending upon the excitation energy, the excited prefragment may decay by emitting one or more nucleons (protons or neutrons), composites (deuterons, tritons, ^{3}He, or alpha particles), or gamma rays. The probability α_{ij} for forming a particular fragment of type i as a result of the deexcitation of a prefragment of type j is obtained from the EVAP-4 computer code (ref. 9) by treating the prefragment as a compound nucleus with an excitation energy given by equation (12). The final fragmentation cross section for production of the type i isotope is then given by

$$\sigma_F(Z_i, A_i) = \sum_j \alpha_{ij}\ \sigma_{abr}(Z_j, A_j) \tag{13}$$

The $\sigma_{abr}(Z_j, A_j)$ values are obtained from equation (1) by setting

$$\sigma_{abr}(Z_j, A_j) = \sigma_{nz} \tag{14}$$

where

$$Z_j = Z - z \tag{15}$$

and

$$A_j = A - m \tag{16}$$

FRAGMENTATION RESULTS

Table II displays the cross section results obtained from equations (1) and (13) for ^{16}O projectiles at 2.1 GeV/nucleon colliding with a ^{208}Pb target. Also displayed are the experimental isotope production cross sections from the fragmentation experiments described in reference 3. Despite the crude and unsophisticated nature of

TABLE II.- ABRASION AND FRAGMENTATION CROSS SECTIONS FOR THE REACTION $^{16}O + ^{208}Pb \rightarrow ^{A}Z + X$

[Incident kinetic energy is 2.1 GeV/nucleon]

Species, ^{A}Z	$\sigma_{abr}(Z,A)$, mb	$\sigma_F(Z,A)$, mb	σ_{exp} (ref. 3), mb
^{15}O	202	202	135 ± 22
^{14}O	53	0	2.8 ± 1.5
^{13}O	17	17	
^{12}O	5	0	
^{11}O	1.5	0	
^{15}N	202	202	202 ± 26
^{14}N	120	120	71 ± 22.5
^{13}N	66	53	17 ± 3
^{12}N	33	0	
^{11}N	15	.6	
^{14}C	53	53	12.3 ± 2.2
^{13}C	66	0	45.4 ± 8.3
^{12}C	58	132	126 ± 25
^{11}C	43	33	36.9 ± 5.7
^{10}C	26	4.3	7.21 ± 1.40
^{13}B	17	0	0.7 ± 0.4
^{12}B	33	17	3.98 ± 0.75
^{11}B	43	33	52.8 ± 5.9
^{10}B	42	85	35.2 ± 11.3
^{9}B	35	3	

these fragmentation calculations, the overall agreement between theory and experiment is quite good. Two main sources of error are the input excitation energy estimate and the assumption of a hypergeometric distribution. The excitation energy calculation assumed that the excitation energy was independent of the charge or quantum states of the abraded nucleons and also ignored the surface diffuseness of the nuclei. The latter probably accounts for the overestimates of the ^{15}O and ^{14}N cross sections, since the excitation energies of these species were too small for any particle evaporation to occur. The most apparent example of the error due to the hypergeometric distribution assumption is the overestimate of the ^{13}O cross section. The use of this assumption resulted in a clearly unphysical 10-percent probability that the three abraded nucleons were all neutrons. This is also the likely source for the ^{13}N overestimate, since ^{13}N is produced by evaporation of a proton from ^{14}O, which has a substantial cross section for removal of only two neutrons. The errors in the ^{13}C and ^{14}C cross sections are attributable to the input excitation energy for ^{14}C. The ^{14}C excitation energy (6 MeV) obtained from equation (12) is too small to initiate particle evaporation. If it is increased, however, to ≈9 MeV, then neutron evaporation to ^{13}C can occur. This possibility is further supported by noting that the calculated σ_F for ^{14}C is nearly equal to the sum of the experimental production cross sections for both ^{14}C and ^{13}C.

Comparisons of the predictions of this work with those of the geometric abrasion-ablation model of reference 8 and the experimental results of reference 3 are shown in table III, where the cross sections for production of nitrogen, carbon,

TABLE III.- ISOTOPE PRODUCTION CROSS SECTIONS FOR THE REACTION $^{16}O + ^{208}Pb \rightarrow Z + X$

[Incident kinetic energy is 2.1 GeV/nucleon]

Process	Isotope production cross sections, mb		
	Geometric model (ref. 8)	This work	Experiment (ref. 3)
O → N	419	375	290 ± 35
O → C	286	223	228 ± 27
O → B	239	138	93 ± 13

and boron isotopes from oxygen projectile nuclei are given. The production cross sections for a particular nuclear species (e.g., boron) were obtained by summing the contributions from all isotopes for that given species

$$\sigma_F(Z) = \sum_A \sigma_F(Z,A) \tag{17}$$

As can be seen from table III, when the predictions of this work were compared with the experimental values of reference 3, closer agreement was obtained than by comparison with predictions of the geometric model (ref. 8).

Future efforts at improving these and similar fragmentation calculations will center upon improving the method for estimating the prefragment excitation energy following the abrasion process. A more sophisticated quantum mechanical calculation using a weighted sum-rule method (ref. 11) is a possible improvement to this aspect of the theory. In addition, much of the neglected physics, including partitioning of the input excitation energy into rotational and internal degrees of freedom and correlations between neutron and proton distributions, needs to be incorporated.

CONCLUDING REMARKS

Predictions for the production of secondary nuclear species through the fragmenting of ^{16}O projectile nuclei by ^{208}Pb target nuclei are presented and compared with experimental results. Although the theoretical calculations utilize very simple methods to treat the ablation effects, reasonable agreement with experimental data is noted. The major sources of disagreement appear to be attributable to the simple geometric model used to estimate the excitation energies of the projectile prefragments and to the assumption of a hypergeometric distribution, which neglects correlation effects between the neutrons and protons in the nucleus. Clearly, much work remains to be done.

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SYMBOLS

A	nuclear mass number
b	projectile impact parameter, fm
E_{exc}	projectile prefragment excitation energy, MeV
E_s	nuclear surface energy coefficient, MeV
F	defined in equations (5) and (11)
m	number of abraded nucleons
N	total number of nuclear neutrons
n	number of abraded neutrons
P	defined in equations (4) and (10)
R_P	uniform nuclear radius of projectile, fm
R_T	uniform nuclear radius of target, fm
Z	total number of nuclear protons
z	number of abraded protons
$\binom{A}{m}$	binomial coefficient
α_{ij}	probability of formation of type i fragment as a result of deexcitation of type j prefragment
β	defined in equation (7)
Δ	excess nuclear surface area, fm^2
μ	defined in equation (8)
ν	defined in equation (6)
$\sigma_{abr}(Z,A)$	cross section for production of nucleus of type (Z,A) by abrasion, mb
σ_{exp}	experimental cross section
σ_F	fragmentation cross section, mb
σ_m	cross section for abrading m nucleons, mb
σ_{nz}	cross section for abrading n neutrons and z protons, mb

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16. Abstract

Ablation effects in the fragmentation of 2.1 GeV/nucleon oxygen nuclei by lead targets are examined by using the mechanism of particle evaporation. Following the initial abrasion process, the excited projectile prefragment is assumed to statistically decay in a manner analogous to that of a compound nucleus. The decay probabilities for the various particle emission channels are calculated by using the EVAP-4 Monte Carlo computer program. The input excitation energy spectrum for the prefragment is estimated from the geometric "clean cut" abrasion-ablation model. Isotope production cross sections are calculated and compared with experimental data and with the predictions from the standard geometric abrasion-ablation fragmentation model.

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